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NRQCD FACTORIZATION AND QUARKONIUM PRODUCTION AT HADRON-HADRON AND *ep* COLLIDERS

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I review the NRQCD factorization approach for quarkonium production and compare its predictions with measurements in hadron-hadron and *ep* collisions.

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I refer the reader to Ref. 1 as a supplement to this brief account.

1. FACTORIZATION OF THE INCLUSIVE QUARKONIUM PRODUCTION CROSS SECTION

In heavy-quarkonium production in hard-scattering processes, two large momentum scales appear: the heavy-quark mass m and the typical momentum transfer in the hard scattering, which I will denote generically by p_T. One would like to separate the perturbative physics at these large momentum scales from the physics at smaller momentum scales that is associated with nonperturbative heavy-quarkonium bound-state dynamics. It has been conjectured[2] that, for the inclusive quarkonium production cross section at $p_T \gg m$, one can achieve such a separation and that one can write the cross section in the following factorized form:

$$\sigma(H) = \sum_n F_n \langle 0|\mathcal{O}_n^H|0\rangle. \tag{1}$$

The F_n are "short-distance coefficients." They are essentially the process-dependent partonic hard-scattering cross sections convolved with the parton distributions. The partonic hard-scattering cross sections depend only on the large scales m and p_T, and they have an expansion in powers of α_s. The quantities $\langle 0|\mathcal{O}_n^H(\Lambda)|0\rangle$ are long-distance matrix elements (LDMEs) that are formulated in terms of the effective field theory nonrelativistic QCD (NRQCD). They give the probability for a heavy $Q\bar{Q}$ pair with a certain set of quantum numbers to evolve into a heavy quarkonium H.

The LDMEs have a known scaling with v, the heavy-quark velocity in the quarkonium rest frame. Hence, the factorization formula in Eq. (1) is a double expansion in powers of α_s and v. In practice, the sum in Eq. (1) is truncated at a finite order in v. The LDMEs are believed to be universal (process independent)—an assumption that gives the factorization formula much of its predictive power.

A key feature of NRQCD factorization is that quarkonium production can occur through color-octet, as well as color-singlet, $Q\bar{Q}$ states. If one drops all of the color-octet contributions and retains only the leading color-singlet contribution, then one obtains the color-singlet model (CSM). The CSM is inconsistent for production processes beyond leading order in v, for example, production through P-wave $Q\bar{Q}$ channels, because it leads to uncanceled infrared divergences.

1.1. *Status of a Proof of Factorization*

A proof of the NRQCD factorization formula in Eq. (1) is complicated because gluons can dress the basic production process in ways that apparently violate factorization, for example, by connecting one incoming hadron to another or by connecting an incoming hadron to the quarkonium. A proof of factorization would involve a demonstration that diagrams in each order in α_s can be re-organized so that (1) all soft singularities cancel or can be absorbed into NRQCD matrix elements and (2) all collinear singularities and spectator interactions can be absorbed into parton distributions.

Nayak, Qiu, and Sterman pointed out that, in order to make the color-octet NRQCD LDMEs gauge invariant, one must be modify them from the original definition[2] by including eikonal lines (path-ordered exponentials of path integrals of the gauge field) that run from the points at which the $Q\bar{Q}$ pair is created to infinity.[3,4] These eikonal lines are essential at two-loop order in order to allow certain soft contributions to be absorbed into the LDMEs. However, they do not affect existing phenomenology, which is at tree order or one-loop order in the case of the color-octet channels. A key difficulty in proving factorization to all orders in α_s is the treatment of gluons that have momenta of order m in the quarkonium rest frame. Such gluons can communicate with the $Q\bar{Q}$ pair through the exchange of soft gluons, which lead to infrared divergences. One could absorb these infrared divergences into the LDMEs by treating the gluon with momenta of order m as an eikonal line in each LDME. However, such a treatment would preserve the universality of the LDMEs only if they are independent of the direction of the eikonal line (the direction of the gluon). In an explicit calculation at two-loop order, the dependence on the direction of the eikonal line cancels.[3,4] However, it is not known if this cancellation generalizes to all orders. An all-orders proof of factorization is essential because non-factorizing soft-gluon contributions, for which α_s is not small, could be important numerically at any order.

Nayak, Qiu, Sterman have also pointed out that, if an additional heavy quark is approximately co-moving with the $Q\bar{Q}$ pair that evolves into the quarkonium,

then there can be soft color exchanges between the heavy quark and the $Q\bar{Q}$ pair.[5] This process does not fit into the NRQCD factorization picture because it involves LDMEs that contain additional heavy quarks beyond the $Q\bar{Q}$ pair that evolves into the quarkonium. The process is nonperturbative and, therefore, its rate cannot be calculated reliably. However, the process can be identified experimentally. Its signature is an excess of heavy-flavor mesons in a cone around the quarkonium of angular size of order mv divided by the quarkonium momentum.

2. Quarkonium Production in Hadron-Hadron Collisions

It has been known for many years that the cross sections differential in p_T for the production of the J/ψ, $\psi(2S)$, χ_{cJ}, and Υ states at the Tevatron can be fit well by the predictions of NRQCD factorization at leading order (LO) in α_s. The existing fits have included the contributions from the LDMEs of leading order in v in the color-singlet and color-octet channels, and, in the S-wave case, the two independent color-octet LDMEs of the first subleading order in v. The color-singlet LDMEs can be fixed by decay rates, but the color-octet LDMEs are treated as free parameters. While NRQCD factorization passes the minimal test of fitting the Tevatron cross sections, it is important to make more stringent tests by using the fitted values of the LDMEs to predict quarkonium production rates in other processes and to predict values for other observables, such as quarkonium polarizations.

At LO in α_s, NRQCD factorization predicts that prompt J/ψ and $\psi(2S)$ polarizations at the Tevatron should be substantially transverse for values of the quarkonium p_T that are greater than m_c.[6] This prediction is compatible, within uncertainties, with the CDF Run I measurement,[7] but is incompatible with the CDF Run II measurement.[8] The Run I and Run II results are also mutually inconsistent, but the CDF collaboration endorses the Run II results. The CDF Run II data for the $\psi(2S)$ polarization[8] are also incompatible with the LO NRQCD prediction. In the case of Υ polarization, the CDF[9] and D0[10] measurements are incompatible with each other and with the LO NRQCD prediction.[11] The discrepancies between theory and experiment with regard to polarization present a significant challenge to our understanding of the mechanisms of quarkonium production. Comparisons of predictions for the polarization of the J/ψ with experimental measurements are greatly complicated by the presence of feeddown contributions from the $\psi(2S)$ and χ_{cJ} states. Measurements the polarization of the J/ψ in direct production would be of considerable help understanding the production mechanisms.

In the case of quarkonium production in the color-singlet channel, complete corrections at next-to-leading order (NLO) in α_s and real-gluon corrections at next-to-next-to-leading order in α_s (NNLO*) have been calculated. These calculations have revealed the surprising result that, at large p_T, higher-order contributions can be enhanced by more than an order of magnitude relative to lower-order contributions because the higher-order contributions fall off less rapidly as p_T increases.[12,13] In the case of prompt J/ψ production at CDF[14], the NNLO* color-singlet contribution[15]

lies well below the data, suggesting that most of the cross section comes from a color-octet contribution. In the case of prompt Υ production at CDF,[16] the NNLO* color-singlet contribution[13] could explain the data by itself. However, the large theoretical uncertainties still allow the presence of a substantial color-octet contribution. In the case of J/ψ production at STAR[17] and at PHENIX,[18] the NLO and NNLO* color-singlet corrections are large,[19] and the upper limit of the large uncertainty band for the NNLO* prediction is close to the STAR data at large p_T.

NLO calculations of the $^1S_0$ and $^3S_1$ color-octet contributions to S-wave quarkonium production at the Tevatron and the LHC show that the corrections to J/ψ and $\psi(2S)$ production are less than 25%,[20] while the corrections to Υ production are less than 40%.[21] Recently, two groups have completed the first NLO calculations that include all of the color-octet channels through the first subleading order in v.[22,23] The numerical results of the two groups for the short-distance coefficients are in agreement and show a very large negative K factor in the ^3P_J channels. In Ref. 23, the LDMEs were extracted in a fit to both the CDF Run II data[14] and the H1 photoproduction data,[24,25] and the resulting LDMEs are not qualitatively different in size from those that were obtained in LO fits to the Tevatron data. In Ref. 22, fits were made only to the CDF Run II data,[14] and two linear combinations of LDMEs were determined. The fitting procedures that were used in Refs. 22 and 23 differ in a number of respects, beyond the inclusion/exclusion of the H1 data, and the LDMEs that were obtained differ substantially, in one case by an order of magnitude. Clearly, it will be necessary to examine the validity of the assumptions that are implicit in the fitting procedures before any conclusions can be drawn about the sizes of the LDMEs. In Refs. 22 and 23, the extracted values of the LDMEs were used to make predictions for the prompt J/ψ cross section differential in p_T at CMS,[26] and good agreement was obtained. In Ref. 23, a prediction was also made for the J/ψ cross section at PHENIX,[27] and good agreement was again obtained. The fact that good agreement with the CDF and CMS data was obtained using very different values of the LDMEs suggests that the hadroproduction cross section differential in p_T is rather insensitive to the details of the production mechanism.

NLO and NNLO* calculations of the color-singlet contribution to the J/ψ and Υ polarizations reveal that they change from transverse to longitudinal once one goes beyond LO.[13,28,29] NLO corrections to the color-octet S-wave contributions to the J/ψ polarization produce only small effects.[20] Given the large sizes of the NLO corrections to the rates from color-octet ^3P_J channels, it is clearly necessary to compute the contributions to the polarization from these channels before a definitive comparison can be made between NRQCD factorization predictions and experiment.

The large corrections that occur at NLO and NNLO* cast some doubt on the convergence of the perturbation series. As I have mentioned, the large corrections arise, at least in part, because the NLO and NNLO* contributions in certain $Q\bar{Q}$ channels fall more slowly with p_T than do the lower-order contributions. The p_T distribution can fall no more slowly than $1/p_T^4$. This dependence is achieved in the color-singlet channel at NNLO* and in the color-octet channels at NLO. Hence, no further kine-

matic enhancements are expected beyond these orders. However, the theoretical uncertainties are large in these orders because the kinematically enhanced contributions are, in effect, computed at the Born level. Kang, Qiu, and Sterman have suggested that this difficulty might be overcome by using fragmentation-function methods to reorganize the perturbative calculation according to the p_T dependence of the contributions.[30] Such a reorganization might make it possible to compute more accurately the contributions that are most important numerically.

3. Quarkonium production in *ep* collisions

Until recently, it had been believed that NLO color-singlet contributions account quite well for the J/ψ photoproduction cross sections that have been measured at HERA, leaving little room for a color-octet contribution.[31,32] However, a new calculation of the NLO color-singlet contribution,[33] while confirming the analytic results of the previous calculations, reveals that a more reasonable choice of the renormalization/factorization scale yields a much smaller numerical value for the color-singlet contribution, thereby opening the possibility that there is an appreciable color-octet contribution. This possibility was substantiated by a complete NLO analysis, including color-octet contributions,[23,34] in which it was found that color-octet contributions are necessary in order to obtain agreement with the H1 data.[24,25] While the NLO cross section differential in p_T is in good agreement with the H1 data, the NLO cross section differential in the J/ψ energy fraction z deviates from the data at low and high z. However, these deviations are understood as arising from the presence of uncalculated resolved-photoproduction contributions at small z and the failures of convergence of the NRQCD velocity expansion and the perturbation expansion near $z = 1$, both of which require a resummation in order to obtain reliable predictions.

The color-singlet contribution to the J/ψ polarization in photoproduction is strongly affected by QCD corrections,[33,35] changing from largely transverse at LO to largely longitudinal at NLO. Comparisons of the NLO color-singlet contribution with the H1 and Zeus data[36,37] show that the color-singlet contribution alone cannot explain the observed polarization. A complete NLO calculation, including color-octet contributions, would be necessary in order to make a meaningful comparison between the predictions of NRQCD factorization and the data.

An LO calculation of J/ψ production in deep-inelastic scattering at HERA is generally in good agreement with the data.[38] However, given the importance of NLO corrections in other quarkonium production processes, it would be prudent to wait for the calculation of the NLO corrections to deep-inelastic scattering before drawing any conclusions.

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